Assessing the Reliability and Economics of Wide-Scale Grid-Connected Distributed Energy Generation with Application to Electric Power Systems Under Stress

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Hisham Zerriffi
Carnegie Mellon University

More Info: hisham@cmu.edu

Outline

- The Need for Robust Infrastructures
- Engineering Robustness
- Socio-Political and Institutional Factors
- Engineering-Economic Model

The Need For Robustness

- We depend on inter-connected, complex systems that are inherently vulnerable
  - Electricity enables almost every facet of modern life (e.g. TV), and many essential features (e.g. water supply, traffic lights and telecommunication)
  - Interdependencies with fuel supply and Supervisory Command And Data Acquisition (SCADA) systems
- Complex systems seem to have more large-scale disruptions than standard statistical fit would suggest (the pdf has a fat tail).
- Suggests that the only strategy is to accept that vulnerabilities will always exist, that failures (even large ones) will always occur. But still want to design robustness into our systems to minimize impact of unforeseen events

Engineering Robustness

- Reliable – System will meet given performance characteristic under ordinary operations
- Robust – The ability of a system to continue to function under exceptional circumstances
- MTTF – Mean Time to Failure and MTTR – Mean Time to Repair
- Increase MTTF and/or decrease MTTR of system components and availability increases – but still dependent on same technology (other operating characteristics – size/speed, etc)
- Change system architecture and robustness *may* increase. But can also imply changes to social components of the system
- Engineers generally use standard models and codified practices for reliability planning – many unstated assumptions

Socio-Political & Institutional Factors

- Engineered Systems are located within specific socio-political and institutional contexts
  - We have to consider these factors in both design and evaluation of engineered system components and architectures.
- Robust System must handle various types of stress
  - Both Technical and Non-Technical Stresses
  - Non-technical stresses are not captured necessarily in engineering criteria
- Engineered Systems are governed by social institutions
  - Creates incentives/disincentives for investing in robustness
  - Establishes the mechanisms for allocating cost

Integrated Robust Energy System Design

- Have to account for multiple infrastructure components
  - Electricity system, architecture and its sub-components (e.g. generating units)
  - Fuel supply
- Have to account for socio-political context
  - expected source and nature of disturbances
  - impacts of disturbances
  - resources
  - Non-technical drivers
- Have to account for regulatory and business structure
  - State owned monopolies
  - private regulated monopolies
  - market based competition
  - How are public goods (like robust infrastructures) financed?

Context Matters

	More Industrialized / Least Risk	Less Industrialized / Most Risk
Electricity planning	Conflict rarely considered	Conflict rarely considered
Type of conflict	Systematic terrorism	War or terrorism
Electricity infrastructure	Existing	Growing
Natural gas infrastructure	Existing	Growing
Finance	Available	Sparse
Engineering skills	Available	Sparse
Replacement parts	Available	Sparse
Economic loss	Likely High in Absolute Terms	Likely High in Relative Terms
Threat to human health	Possible	Likely

Mode of Disturbance	Possible Causes	Likely Characteristics	Likely Impacts
Weather Related Damage	Hurricanes, tornadoes, floods, ice storms	Random, not repeated, not targeted, regional	Impacts T&D primarily. No long term impacts on failure probabilities, magnitudes or durations. Recovery only hampered by environmental conditions
System-wide Direct Conflict Damage	Civil War (e.g. Bosnia), guerilla movement	Persistent, system-wide, impacts all levels of system	Both failure probabilities and magnitude of damage high, recovery difficult and expensive due to continuing conflict
Regional Direct Conflict Damage	Regional Insurgency	Persistent but localized, impacts all levels of system	Failure probabilities and magnitudes increase in affected region, recovery difficult
Localized Direct Conflict Damage	Terrorism/Sabotage	targeted, repeated (lower frequency), less damage per attack on average, less damage to large generators	Failure probabilities increase, magnitudes do not increase greatly except for the most extreme acts, recovery relatively unhampered
System-wide Indirect Conflict Damage	Civil War (e.g. Bosnia), guerilla movement	Mobility hampered, increased non-technical losses creating financial problems	Failure probabilities increase, magnitude of failures do not increase, recovery more difficult
Regional Indirect Conflict Damage	Regional Insurgency	Regional mobility hampered, increased non-technical losses, financial problems	Failure probabilities increase, magnitude of failures do not increase, recovery more difficult
Lack of Investment in New Capacity	Capital access, investment uncertainty	Units need to be run more often and for longer as reserve margins decline	Possible increase in failure rates over time
Poor Maintenance	Capital and spare parts access		Failure rates increase over time, repair times increase

Mode of Disturbance	**Previous Literature**	**Possible Modeling Options**
Normal Operating Conditions	Extensive. OECD focused.	Established simulation and analytic methods
Weather	Extensive	Already included in models
System-wide Direct Conflict Damage	Focus on OECD. Older literature on nuclear security.	Unit availability adjustment. Application to multiple system architectures
Regional Direct Conflict Damage	Focus on OECD (limit to damage due to size of system). Focus on Physical and Cyber Protection. DG benefits qualitatively described.	Unit availability adjustment in affected area
Localized Direct Conflict Damage	Focus on OECD. Focus on Physical and Cyber Protection. DG benefits qualitatively described	Unit availability adjustment, spatial distribution of attacks according to Poisson distribution
System-wide Indirect Conflict Damage	Limited. Focus on "terror" aspects (e.g. nuclear)	Unit availability adjustment
Regional Indirect Conflict Damage	Limited. Focus on "terror" aspects (e.g. nuclear)	Unit availability adjustment in affected area
Lack of Investment in New Capacity	Restructuring literature	Increase demand, slowly increase failure rates over time
Poor Maintenance	Literature on rehabilitation of rural networks in developing world.	Unit availability adjustment (perhaps a dynamic model with decreasing availabilities over time)

Engineering-Economic Analysis of System Architectures

- Goal: To quantify and compare the reliability and economics of centralized and distributed electric power systems, particularly under conditions of high stress.
- Techniques:
  - Industry standard Monte Carlo reliability simulation
  - Cost of electricity calculation
  - Accounts for both reliability and cogeneration
  - Economic comparisons of centralized and distributed systems.
- Contribution: Many claims concerning robustness of distributed generation but without quantification of reliability benefits and costs.

Systems Compared

- Centralized
  - Based on IEEE RTS
  - 32 Generators (12-400 MW)
  - Mix of fuels (coal, nuclear, oil, gas)
  - Mix of unavailabilities
- Distributed
  - Internal combustion engines with cogeneration
  - 500 kW
  - Natural gas fired
  - Base unavailability of 0.047
  - Assumed use of ½ waste heat for cogeneration

Natural Gas Network

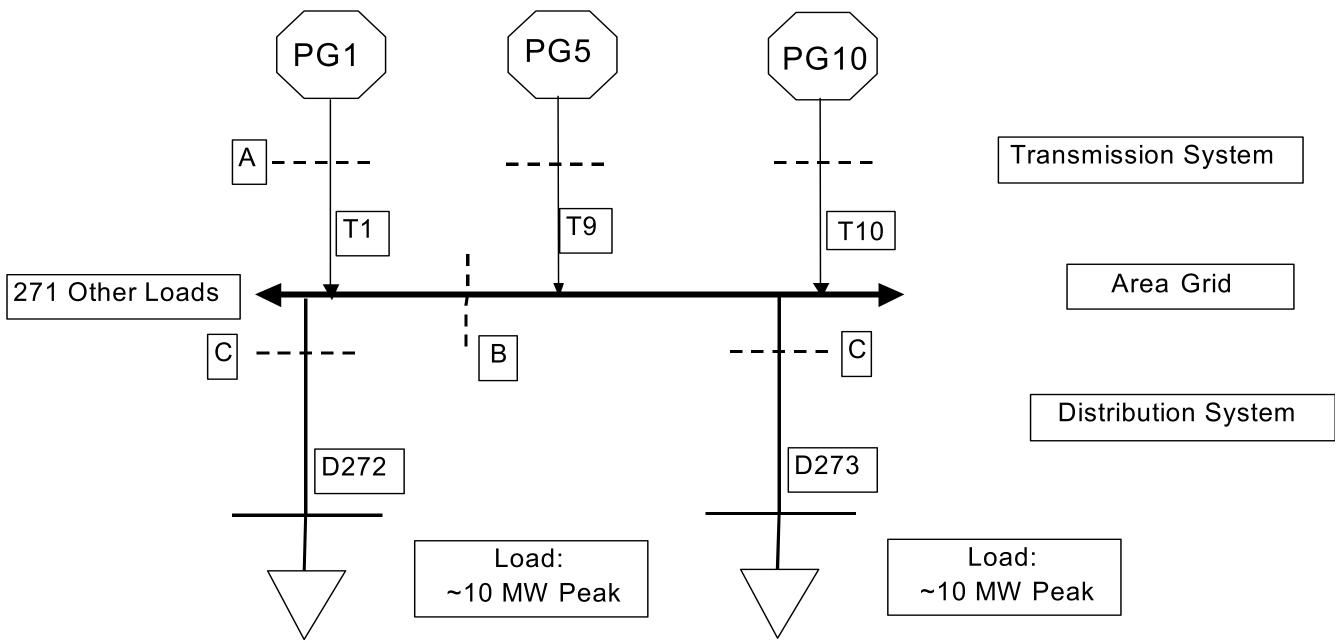
- Seven storage areas
- 200 miles of pipeline from storage to city gates
- 13 city gates
  - Each served by two storage areas
- 3 sub-transmission mains per city gate (10 miles long)
  - Radial and non-redundant
  - Seven micro-grids per main

Generating Technologies, Capacities, Unavailabilities and Assigned Power Group

Unit #	Capacity	Unavailability	Power Group	Technology	Old Technology
1-3	12	0.02	5	Oil/Steam	Oil/Steam
4-5	100	0.04	3	Oil/Steam	Oil/Steam
6-8	197	0.05	4	Oil/Steam	Oil/Steam
9	20	0.1	1	Oil/CT	Oil/CT
10	20	0.1	2	Oil/CT	Oil/CT
11-13	50	0.1	9	Oil/CT	Hydro
14-15	12	0.065	5	CCGT	Oil/Steam
16	20	0.065	1	CCGT	Oil/CT
17	20	0.065	2	CCGT	Oil/CT
18-20	50	0.021	9	CCGT	Hydro
21	76	0.021	1	CCGT	Coal/Steam
22	100	0.058	3	CCGT	Oil/Steam
23	155	0.058	5	CCGT	Coal/Steam
24	76	0.02	1	Coal/Steam	Coal/Steam
25-26	76	0.02	2	Coal/Steam	Coal/Steam
27	155	0.04	6	Coal/Steam	Coal/Steam
28-29	155	0.04	10	Coal/Steam	Coal/Steam
30	350	0.08	10	Coal/Steam	Coal/Steam
31	400	0.12	7	Nuclear	Nuclear
32	400	0.12	8	Nuclear	Nuclear

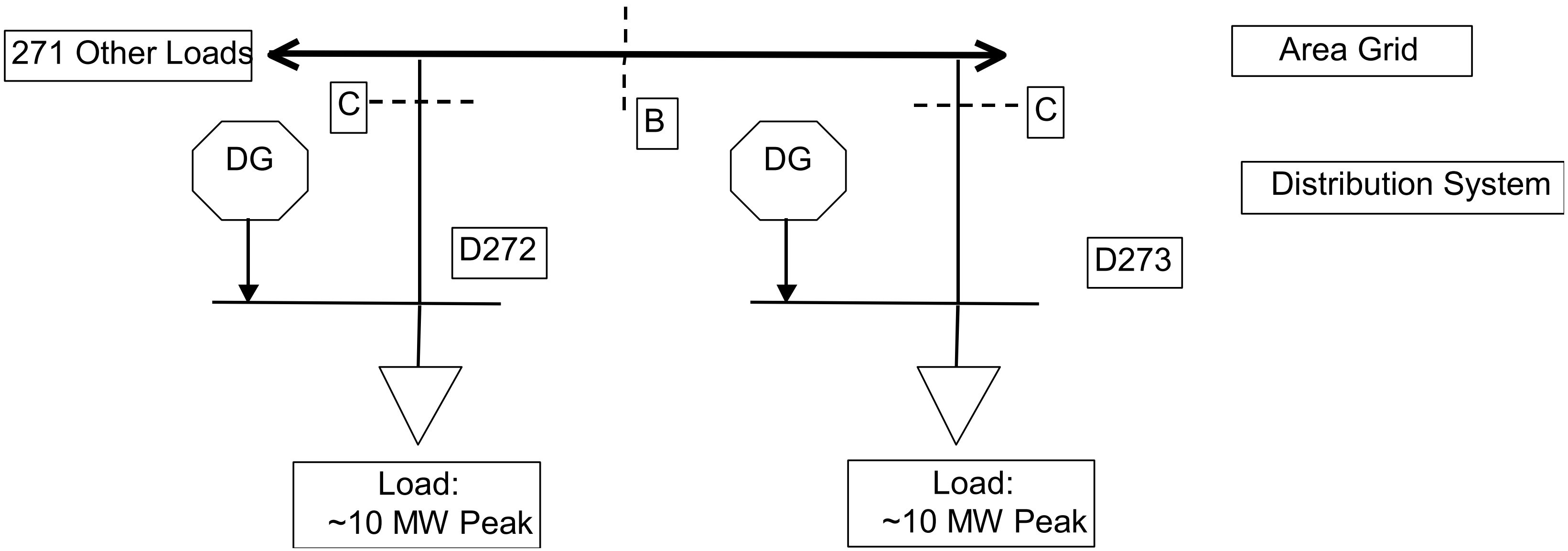
System Topology - Centralized

Total Generation
3405 MW



Total Load
2822 MW

System Topology - Distributed



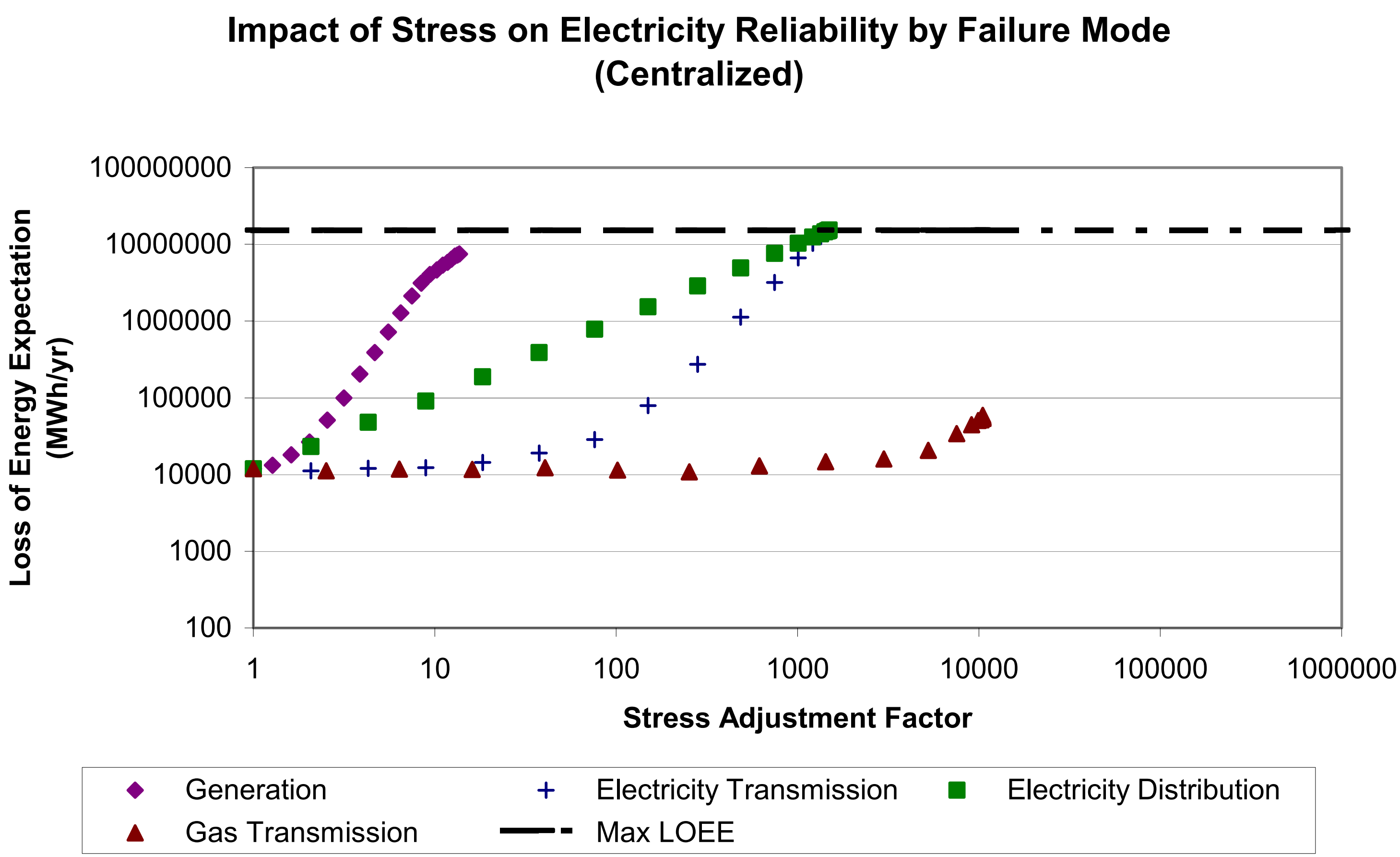
Total Generation
2850 - 3420 MW

Total Load
2850 MW

Robustness of DG and Natural Gas

Features of DG	Conflict Context Advantages
Increased Number and Smaller Size of Generators	When one generator is damaged, a much smaller proportion of the generating capacity is unavailable.
Decreased Reliance on Electricity Transmission and Distribution	The electricity transmission and distribution system is harder to protect than generators. Having generation close to the load reduces the reliance on the vulnerable transmission system.
Underground Natural Gas T&D	Natural gas transmission and distribution systems are generally underground and therefore better protected than electrical transmission and distribution lines.
T&D Real-Time Operational Advantages	Gas pipelines do not have the strict real-time operational problems that electric power grids do such as stability, and there is no gas system analog for cascading failures.
Fuel Substitutability	Some DG technologies have dual fuel capabilities, which mitigates against the impact of replacing a multi-fuel centralized system with a system predominantly reliant on a single fuel.
Fuel Storage	Electricity storage is not economically feasible. Hence, while primary fuel storage (in both centralized and distributed systems) is a security of supply measure, it does not isolate consumers from electricity T&D failures. In the DG system, local fuel storage offers this extra level of security.

Simulation Results



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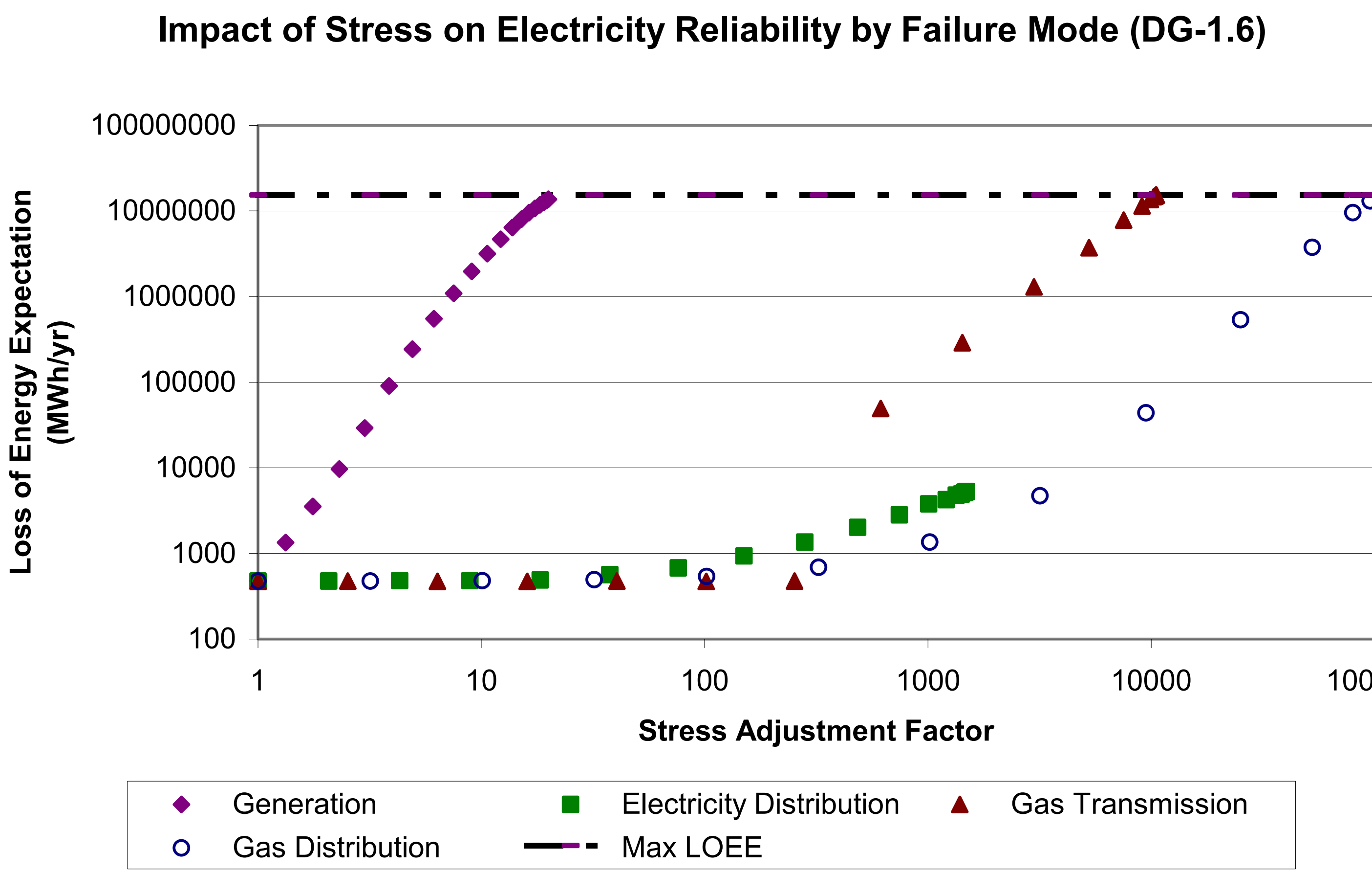

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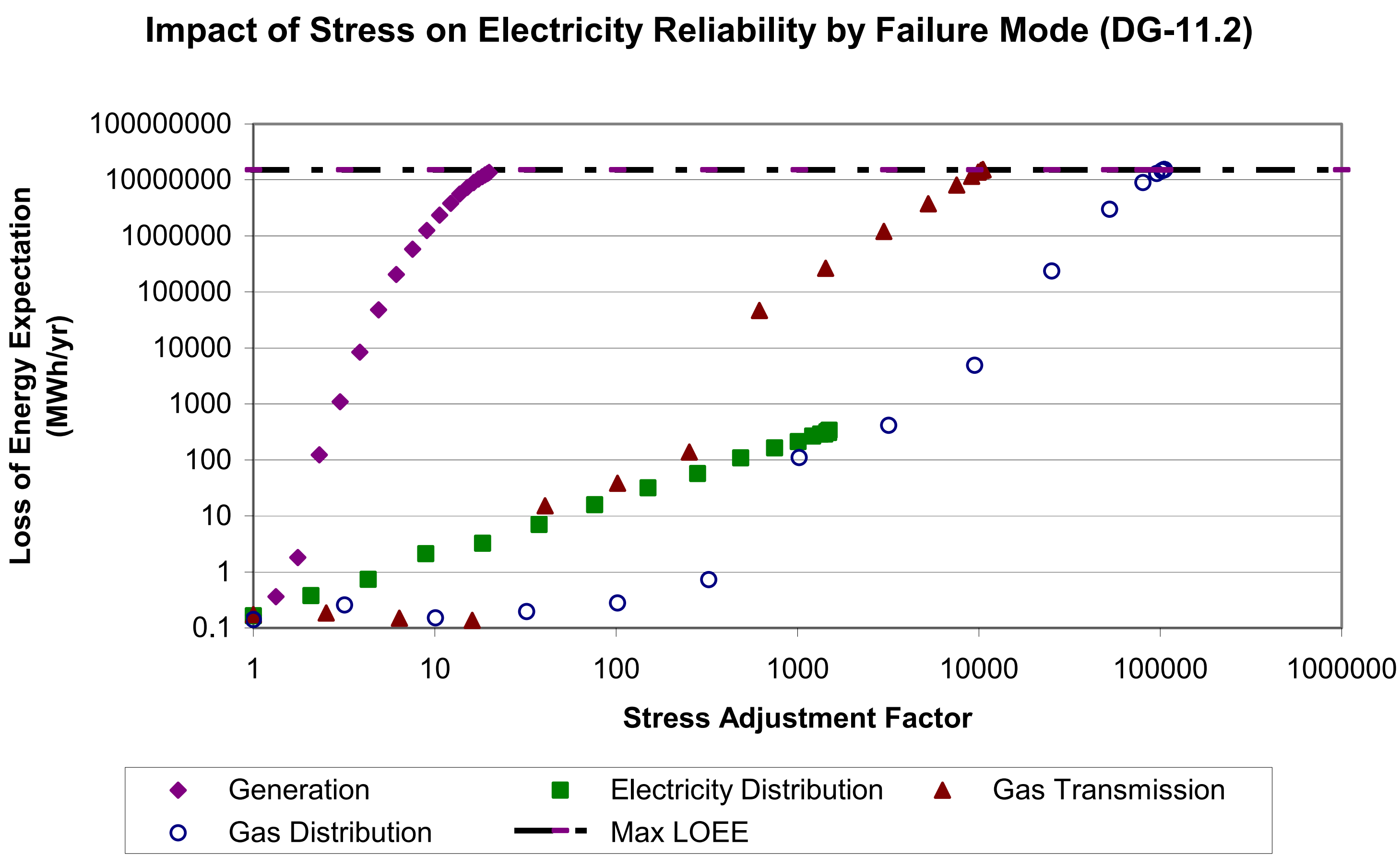

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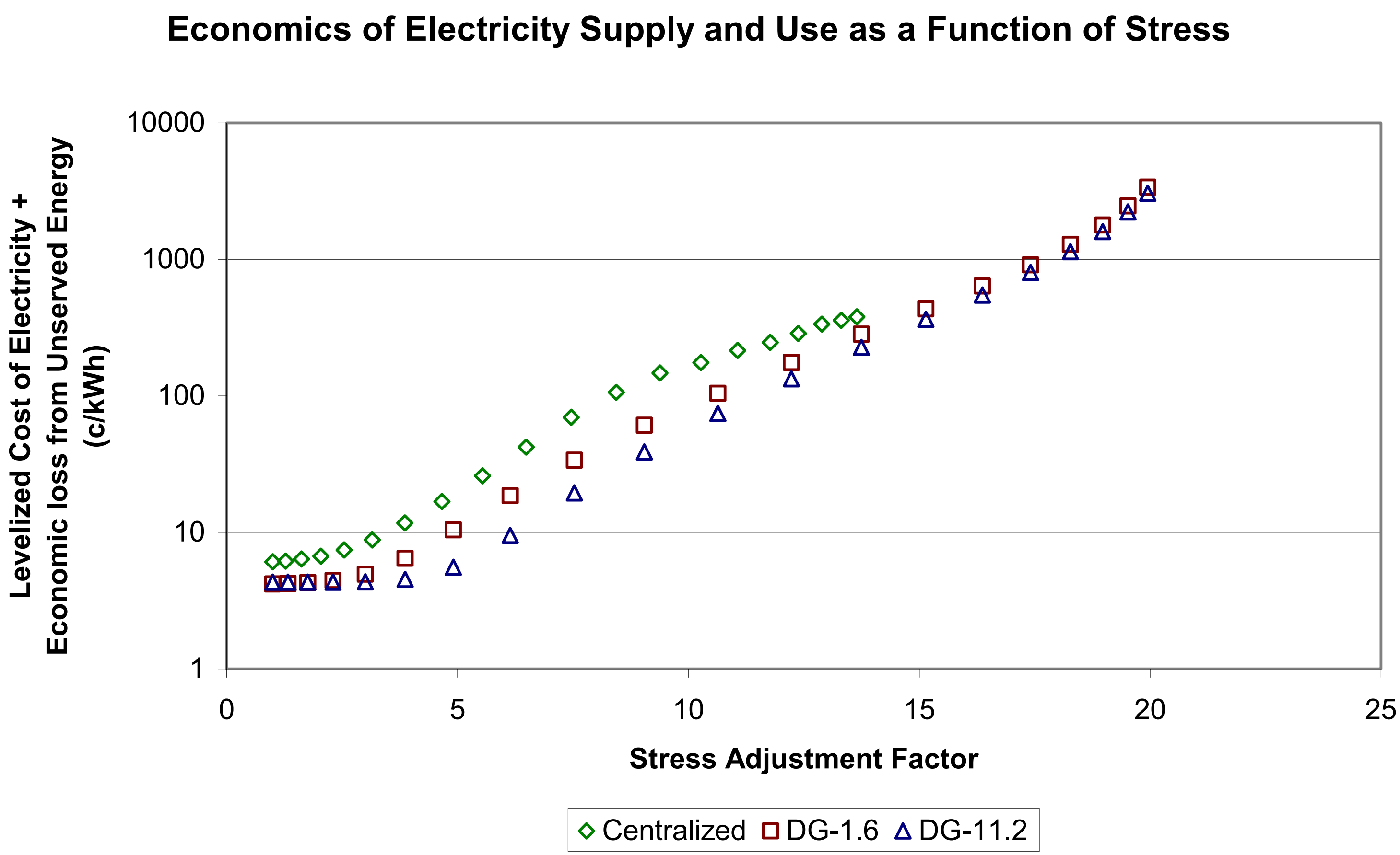

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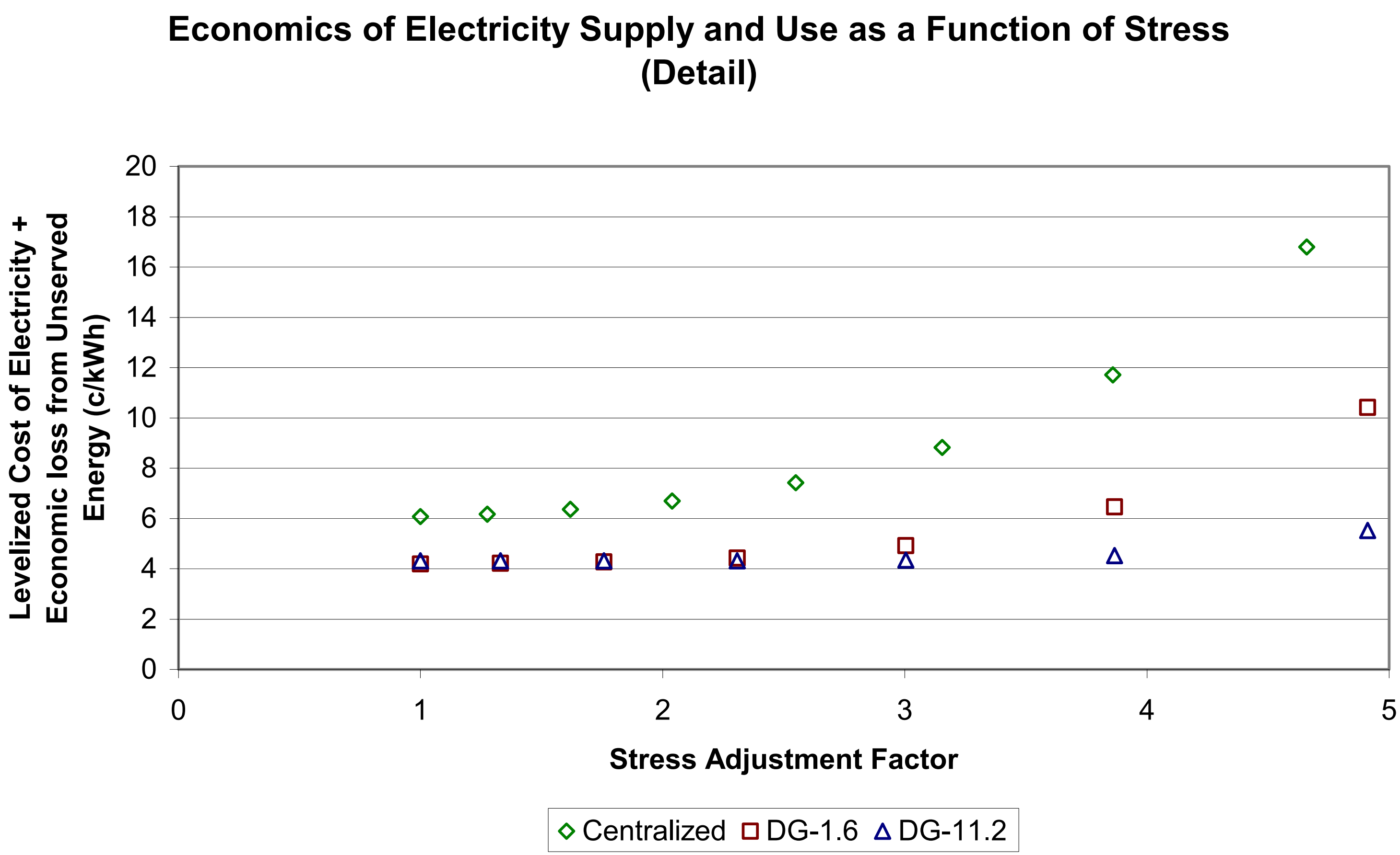

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Description	Size (MW)	Capital ($/kWe)	Fixed OM ($/kWe)	Var. OM (c/kWh)	Fuel Price (c/kWh)	Lifetime (years)	Electricity trans (c/kWh)	Fuel Trans (c/kWh)	Efficiency (%)
CCGT	12-155	536	12.26	0.204	0.891	30	1.606	0.04	55
Oil Turbine	20-50	409	10.22	0.409	1.48	30	1.606	0.13	23
Oil Steam	12-197	409	10.22	0.409	1.48	30	1.606	0.13	20
Coal	76-350	1154	24.52	0.307	0.4	30	1.606	0.08	38
Nuclear	400	2117	58.48	0.043	0.04	30	1.606	-	30
DG	0.5	700	15	0.7	0.891	15	0.203	0.44	29
Boiler	0.5	200	10	0.2	0.891	20		0.44	92

Institutions and Business Structure

- 90% of U.S. electricity infrastructure is in private hands
- Appropriate paradigm: Risk Management
  - How do I measure it and what can I do about it?
  - Standards conundrum: Voluntary actions becoming mandatory
  - Can we expect markets to provide national security?
- Restructuring: Changes that *may* result from restructuring could impact survivability in both positive and negative ways
  - Loss of centralized planning and traditional public interest motivation of electrical engineers and cost-plus economics
  - A <u>more efficient but more complex system</u> possible
  - Changed demand response
  - Distributed generation (increased reliability but with possibility of heterogeneous service)
  - Changed information reporting and recording

Contribution of this Research

- Quantitative evaluation of potential DG benefits
  - Engineering-Economic Model
- Long-term structural changes (e.g. system architecture)
- Non-OECD included
- Inclusion of socio-political factors
  - Palestinian Territories Case Study

Parameters of Systems

Scenario	Number of Units	Unit Sizes (MW)	Total Capacity (MW)	Capacity Reserve (percent)
C (Centralized System)	32	12-400	3405	19.5
DG0 (Minimum System)	5700	0.5	2850	0
DG5	5985	0.5	2992.5	5
DG10	6270	0.5	3135	10
DG15	6555	0.5	3277.5	15
DG20 (Close Match to Centralized System)	6840	0.5	3420	20